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THE AIRR CAR -- A LOW EMISSIONS VEHICLE. PART II

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California University

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PART II

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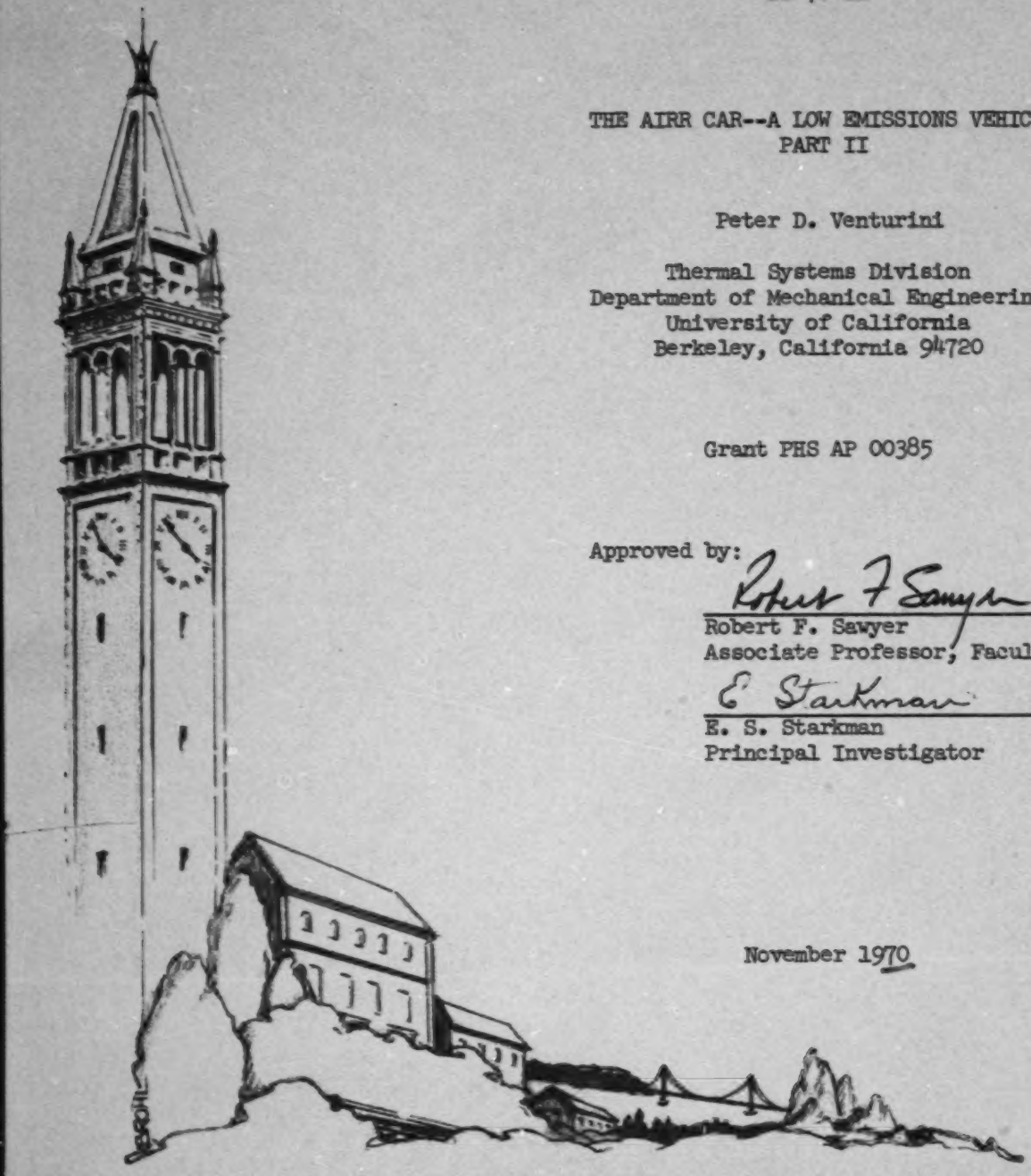

November 1970

COLLEGE OF ENGINEERING

UNIVERSITY OF CALIFORNIA, Berkeley

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PART II

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ABSTRACT

A low emissions vehicle was built and entered in the 1970 Cross Country Clean Air Car Race by a team of Mechanical Engineering students at the University of California at Berkeley. The vehicle finished fourth in class and exhibited exhaust emissions 50 percent below 1975 proposed Federal standards during cold start open seven mode testing. A lack of sufficient development time resulted in some problems with the vehicle; however, its overall performance demonstrated the feasibility of its emissions control system as a viable solution to the automotive pollution problem. The results of these studies are discussed.

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PREFACE

This vehicle is the result of the team effort of six undergraduate students: Peter D. Venturini, Jon L. Nelson, Wayne A. Paulsen, Scott N. Macdonald, Allan Webb, and Juergen Kasprik. The effort was begun in the Winter Quarter of 1970 in a Mechanical Engineering Design Class given by Professors Auslander and Donaldson. The work was continued in a Senior Laboratory under Professor Sawyer. In addition to the assistance from the faculty and the mechanical staff, generous support was given by other individuals and organizations. The author received support as a Research Assistant under NAPCA Grant AP-385-05 during the Summer of 1970.

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INTRODUCTION

The reduction of pollutants from the automobile is a complex problem requiring the interaction of many disciplines. The contributions and cooperation of many members of the technological and scientific community are necessary. The Mechanical Engineering Department of the University of California at Berkeley became involved through efforts of a team of undergraduate engineering students who designed, built, and entered a low emissions vehicle in the 1970 intercollegiate Cross Country Clean Air Car Race. This report covers the performance and characteristics of the AIRR Team's "Clean Machine" which finished fourth in class in the Clean Air Car Race.

This material has been presented in several sections. Section 1 describes the emissions control system; Section 2 covers vehicle performance using the parameters from the Clean Air Car Race; Section 3 deals with problems encountered with the emissions control system; and Section 4 covers emissions testing; Section 5 is an analysis of the post-race teardown and inspection of the emissions control system; and, Section 6 is a summary and conclusion.

The elimination of the dangers and discomforts of air pollution is an important objective. The AIRR Team hopes that its work has contributed to this end.

Section 1

THE EMISSIONS CONTROL SYSTEM

A detailed description of the emissions control system was presented in a previous paper (1). A summary of the system will be given here with emphasis on modifications not covered in the first paper.

A 1970 Plymouth Belvedere four door sedan is the base vehicle to which modifications were made. It is equipped with a two barrel carbureted 318 cubic inch V-8 with a compression ratio of 8.80:1, a three speed automatic transmission, and a 2.76:1 rear axle. The engine was left in stock condition and only external modifications were made to reduce pollutants. These modifications include two exhaust manifold thermal reactors, synchronized air injection, exhaust gas recirculation, a platinum type catalytic muffler, and unleaded gasoline.

The two thermal reactors provide a high temperature enviornment with sufficient residence time for further oxidation of unburned hydrocarbons and carbon monoxide outside of the engine. As raced, the reactors consisted of an outer shell, an insulation layer, and an internal core. Sizing of the reactors was done using a model developed by Schwing (2). The overall dimensions of the reactors is 21 and 3/4 inches long by 4 and 1/2 inches in diameter.

Synchronized air injection is used to supply the necessary excess air to the reactors. A Saginaw air pump delivers air to the synchronizer which distributes this air to each exhaust port in conjunction with exhaust valve opening. The synchronizer is driven at half engine speed by a timing belt from the crankshaft. The drive ratio is 1.7:1.

In the previous paper (1), two types of exhaust gas recirculation systems were described for the reduction of nitrogen oxides. The first used in the vehicle was a log type manifold which injected the recycled gases directly into each intake port. This system required the use of an electrically operated solenoid valve, several switches, and a butterfly valve for control. The solenoid valve soon fell victim to particulates in the exhaust which prevented complete closing of the valve.

In addition, by introducing the recycled gases directly into the intake ports the amount of gas recycled becomes a function of engine intake manifold vacuum. Because of this, the amount of exhaust gas recycled would increase with manifold vacuum which is just the opposite effect from what is desired. The final outcome was to remove this system and install the second alternative system designed for exhaust gas recirculation.

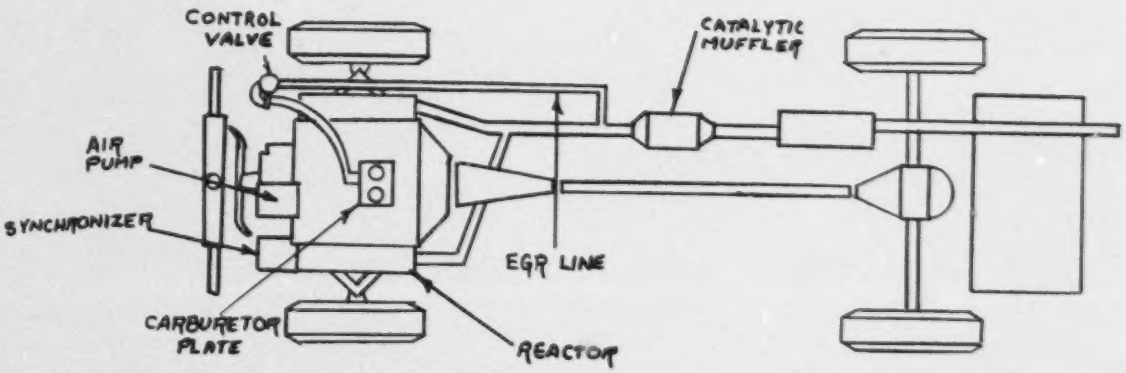
This alternate method of introducing exhaust gases back into the engine utilizes a carburetor plate which fits between the carburetor body and the throttle plate. The plate is made of 3/4 inch aluminum and is drilled to match the two halves of the carburetor where it is inserted. Introduction of recycled gases in this manner, above the throttle plate, results in the recycle fraction not being a direct function of engine vacuum. Instead, the amount of gas recycled is dependent on the resistance of the recycle line and upon the amount of exhaust flow, which is related to intake air flow. Since at idle the exhaust flow is low, the amount recycled is correspondingly small so there was no need to provide a cutoff at idle. This does however cause a slightly rough idle at about 12 inches of engine vacuum.

The Englehard catalytic muffler used is of the platinum type and was originally designed for use on fork lift trucks. The muffler provides a further reduction of unburned hydrocarbons and carbon monoxide by catalytic oxidation in the exhaust system. The muffler is insulated to retain heat and mounted in the exhaust line about four feet from the outlet of the exhaust reactor.

The unleaded fuel used is 95 research octane with the Chevron F310 additive. The use of unleaded fuel is necessary to prevent catalyst poisoning and rapid deterioration of the exhaust reactors and recycle system. Below is a schematic of the emissions control system installed in the vehicle.

FIGURE 1

Schematic of Emissions Control System



EMISSION CONTROL SYSTEM

Section 2

PERFORMANCE IN THE CLEAN AIR CAR RACE

In any competition it is necessary to have a winner and to do this it is essential that there be a formula for choosing this winner. For the Clean Air Car Race (CACR) vehicles were placed in one of six classes depending on their type of motive power.

- Internal combustion engine with fuel in gaseous form (19 vehicles)
- Internal combustion engine with fuel in liquid form (13 vehicles).
- Turbine (1 vehicle)
- Electric hybrid (2 vehicles).
- Electric (3 vehicles).
- Steam (1 vehicle) [1]

A total of 38 cars were listed in the final results. Within each class, vehicles were awarded points according to a scoring formula established by the race committee, (3,4).

$$S=E(P+R+TE)$$

Where:

S=Total Score
E=Emissions Factor
P=Performance Score
R=Race Score
TE=Thermal Efficiency Score

1) Steam car did not compete for points.

A winner in each class was determined as being the entrant having the highest score according to the above formula. In addition to class winners, an overall winner was also chosen.

The AIRR Team vehicle was entered in the internal combustion engine with liquid fuel class. The performance of the car based on the scoring formula will be discussed in the remainder of Section 2.

2.1 Performance Score

The performance score consists of the scores from four different tests.

$$P = B + A + UDC + N$$

Where:

P = Performance Score
B = Braking Score
A = Acceleration Score
UDC = Urban Driving Cycle Score
N = Noise Score

Each of the four tests were weighted at 250 points each maximum, thus making 1000 points a perfect score in performance. Table 1 gives the results of the performance testing for the vehicle.

TABLE 1

Results of Performance Tests

Test	Score
Breaking	188
Acceleration	59
Urban Driving cycle	232
Noise	150
Total	629

2. 1.1 Braking

The braking test was a combination of two controlled stop situations: one from 30 miles per hour to a full stop; and one from 60 miles per hour to a full stop. Braking was done in a 12 foot wide lane where the braking distance was measured for each of the two speeds. Conversion to net deceleration rates was made and points were awarded according to an established scoring curve (Fig 2-C). A score of 188 points was obtained which corresponds to an average net deceleration rate of .788g's. This score resulted in a first in class and a third overall.

2.1.2 Acceleration

The times to accelerate from 0-30 miles per hour, 0-45 miles per hour, and 20-50 miles per hour were measured and a net average acceleration rate was computed. Points were awarded according to the scoring curve (Fig 2-D).

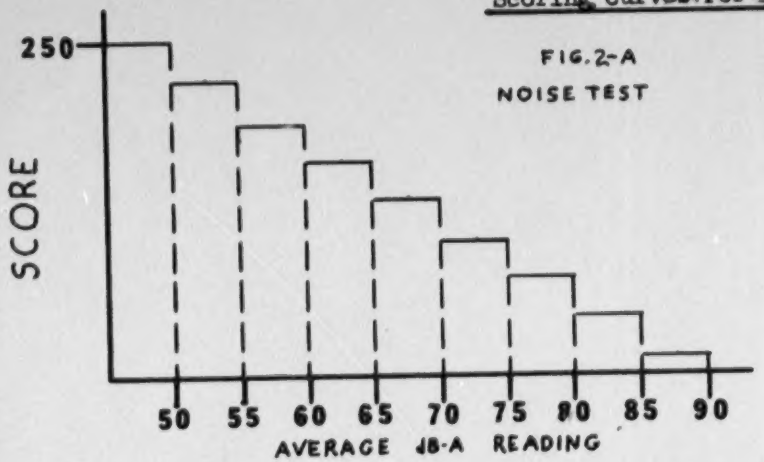
This test was conducted leaving the transmission in the drive position. Faster times would have been possible if a lower gear were used; however, to avoid possible damage to the engine or emissions control equipment, a lower gear was not used. The outcome was a score of 59 points corresponding to a net acceleration rate of .182g's. The result was a seventh in class and sixteenth overall.

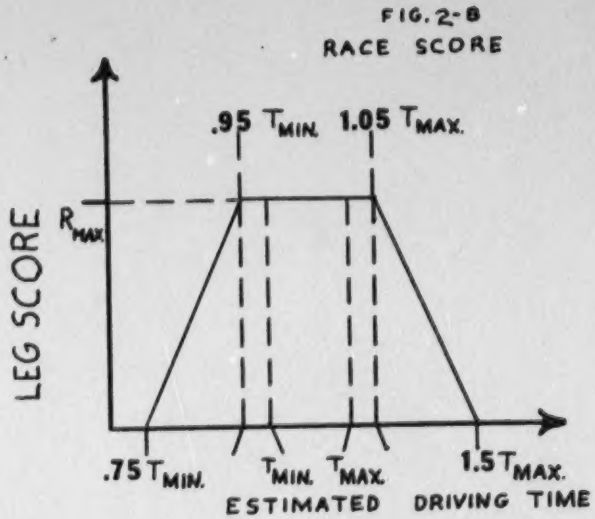
2.1.3 Urban Driving Cycle

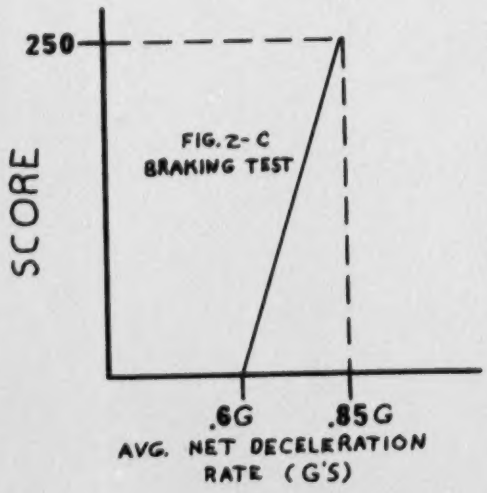
The urban driving cycle consisted of a closed course layed out on a paved surface which would indicate a vehicle's overall handling qualities. Included in the course were straight sections, right and left turns, a lane change condition, and a braking and backing situation.

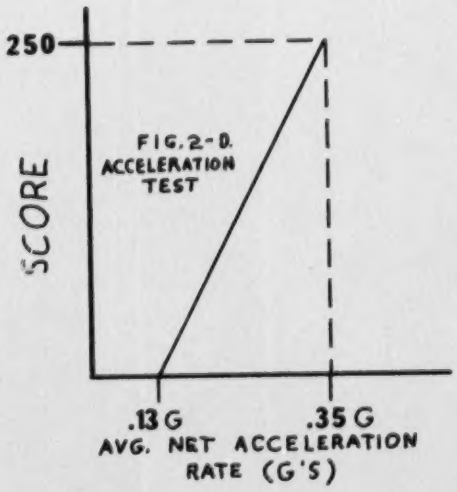
FIGURE 2

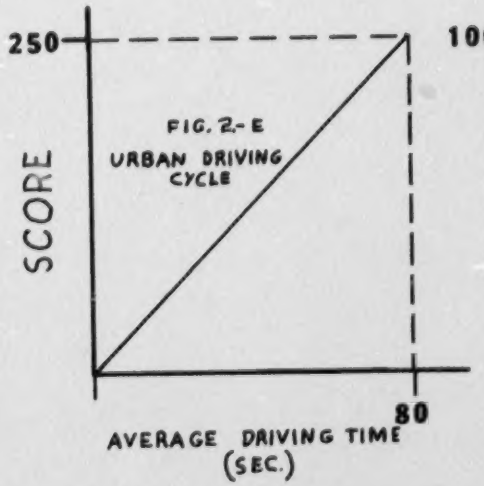
Scoring Curves For The CACR

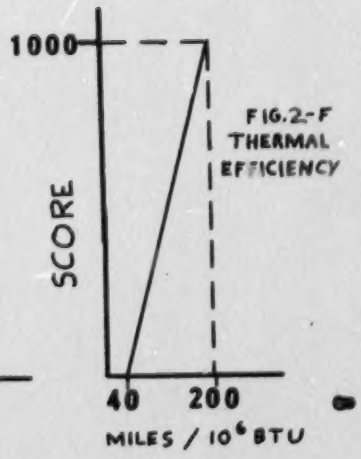












Two members of the driving team were allowed up to three runs each and the best time for each driver was counted. The best time for each driver was taken and the two were averaged then applied to the scoring curve (Fig 2-E). Eighty seconds was the cut-off score for maximum points. The score obtained was 232 points corresponding to an average time of 82.5 seconds. A twelfth in class and twenty-fifth overall was the outcome.

2.1.4 Noise Measurement

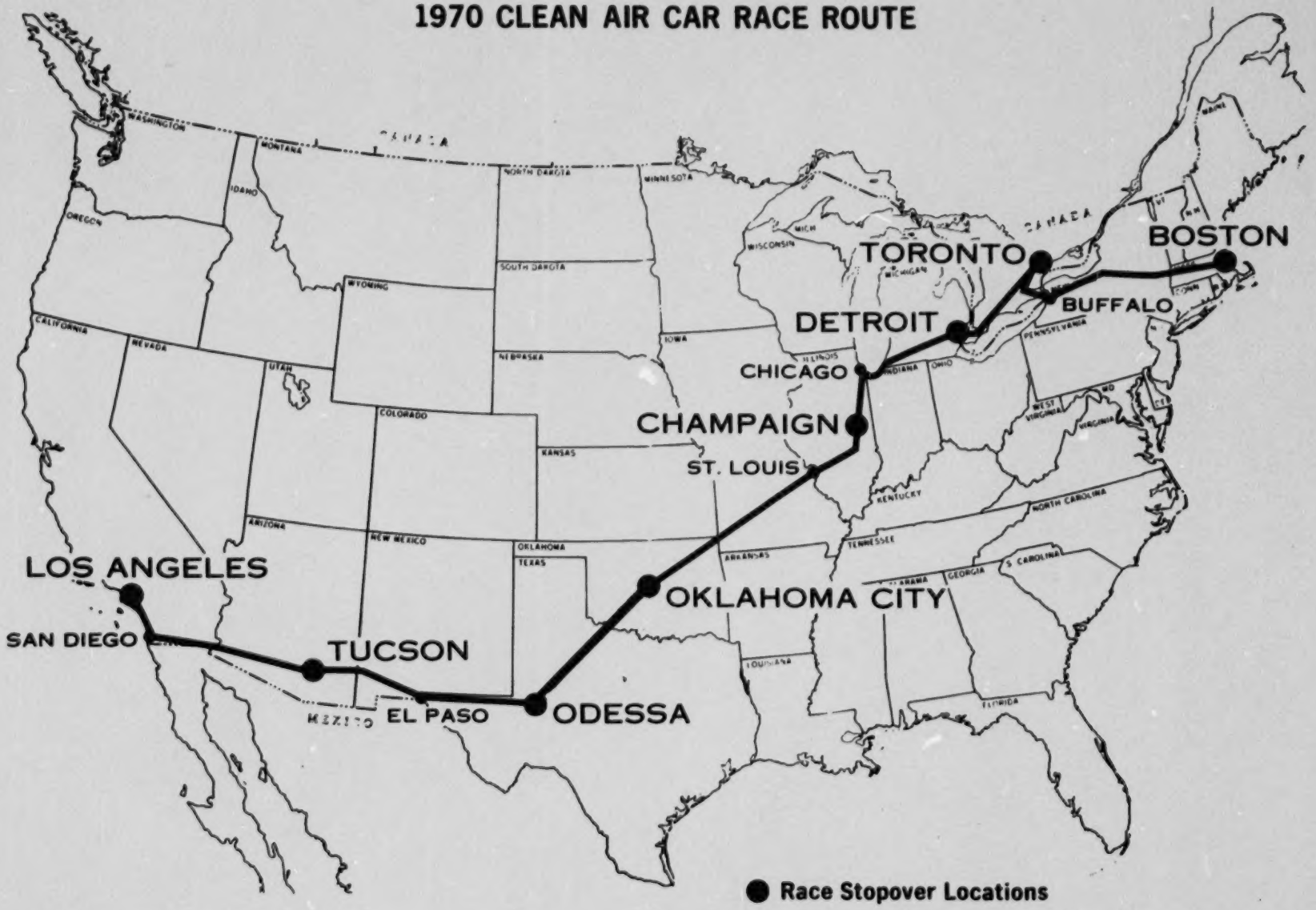
Noise measurements were made according to the procedure specified in SAE J986A. Measurements were made at 30 miles per hour full throttle, 30 mph cruising, 60 mph cruising, and idle. The four db(A) readings were recorded and arithmetically averaged. Points were awarded according to a step curve (Fig 2-A). A score of 150 points resulted in a sixth place in class and an eighteenth overall.

2.2 Race Score

The race itself was conducted much like a time and distance rallye. The 3562 mile route was made up of seven separate legs (See Fig.3). An announced driving time arrived at by comparing AAA times with times obtained by race committee members, was given for each leg. This was the time to strive for to obtain maximum points for a particular leg. The announced driving time was adjusted for meal time (45 minutes for breakfast and 45 minutes for lunch) and for break time (8 minutes for every hour of announced driving time). A sum of the announced driving time, meal time, and break time gave an estimated total driving time for each of the legs of the race.

FIGURE 3

1970 CLEAN AIR CAR RACE ROUTE



Time outs were also allowed under specific circumstances and were not counted in the driving time. Table 2 lists the various times for each leg of the race.

TABLE 2

Times For Each Race Leg (3)

Leg	Announced Driving Time (ADT)	Meal Time	Break Time	Estimated Total Driving Time (TDT)
1	8:50	1:30	1:12	11:32
2	3:45	:45	:32	5:02
3	6:00	1:30	:48	8:18
4	10:55	1:30	1:20	12:45
5	10:20	1:30	1:28	13:18
6	8:50	1:30	1:12	11:32
7	8:15	1:30	1:12	10:57

An observer supplied by the race committee went with each vehicle to keep track of times and report any violations of the rules. A different observer was assigned for each leg of the race.

The race score consisted of the sum of the scores from each of the seven race legs.

$$R=L1+L2+L3+L4+L5+L6+L7$$

Where:
R=Race score
L=Score for a particular leg

The score for each leg was determined by comparing the driving time for a vehicle with an interval about the announced driving time and the normalized driving time (time compiled by the committee during the running of a particular leg). The scoring curve used is shown in (Fig 2-B). The total score achieved was 884 points out of a maximum of 1000. Table 3 summarizes each of the seven legs of the race.

TABLE 3

SUMMARY OF CROSS COUNTRY RACE

Race Leg	Date	From	To	Total Miles	Approximate Total Driving Time	Approximate Average Speed Maintained	Score	Maximum Possible Score
1	August 24	Boston	Toronto	541	9:10	59 mph	150	150
2	August 25	Toronto	Detroit	243	4:01	58 mph	70	70
3	August 27	Detroit	Champaign	403	6:30	62 mph	0	110
4	August 28	Champaign	Oklahoma City	668	10:40	63 mph	190	190
5	August 28	Oklahoma City	Odessa	565	10:00	56 mph	160	160
6	August 29	Odessa	Tucson	605	9:00	67 mph	164	170
7	August 30	Tucson	Pasadena	537	8:00	68 mph	150	150
						TOTAL	884	1000

Points were lost in two instances. No points were given for leg three due to a layover in Detroit for 36 hours. Six points were lost on leg six from arriving too early. The score of 884 points resulted in a twelfth in class and twenty-eighth overall.

2.3 Thermal Efficiency Score

Thermal efficiency was determined for liquid fuel vehicles by measuring the amount of fuel consumed along the race route from Ann Arbor to Oklahoma City, a total of 1071 miles. The weight of five gallon cans used during the race was measured both full and empty, and the number of cans consumed was recorded for the 1071 miles.

Due to a discrepancy in the fuel consumption from Ann Arbor to Champaign, the race committee used only the fuel consumed during the leg from Champaign to Oklahoma City. The amount of fuel consumed was converted to BTU using the higher heating value of the fuel, which for our case (gasoline) was 20,556 BTU/lb., For scoring purposes, the number of miles per million BTU were calculated and the results were applied to a scoring curve (Fig. 2-F)

The limits shown correspond approximately to 5 and 25 miles per gallon. A score of 374 points was awarded, which corresponds to 99.8 miles/ million BTU. The overall fuel consumption was approximately 12.5 miles per gallon. This consisted of almost exclusive high speed (70 miles per hour) turnpike driving.

2.4 Emissions Score

The reporting of emissions was done through the use of an emissions factor E determined by the following formula.

$$E = \frac{1}{\frac{1}{3}\left[\frac{HC}{.5}\left(\frac{HC_p}{HC_b}\right) + \frac{CO}{11}\left(\frac{CO_p}{CO_b}\right) + \frac{NO}{.9}\left(\frac{NO_p}{NO_b}\right)\right]} + PART$$

The HC, CO, and NO are the cold start values in grams/ mile obtained in Detroit. The 0.5, 11.0 and 0.9 values correspond to the 1975 proposed Federal standards. Deterioration factors for each pollutant make up the terms in parentheses; ie. HCp/HC_b, being being the ratio of the hot tests in Boston and Pasadena. Particulate values are included as an additional term (PART). For particulate emissions greater than .1 gms/mile, the term (PART) takes on the value -0.1. If particulates are less than or equal to 0.1 gms/mile, then PART becomes 0.1. Finally, for particulate emissions less than or equal to 0.03 gms/mile, PART becomes 0.2.

The first term on the right of the formula is such that if a vehicle meets exactly the 1975 standards and has a deterioration factor of one for each pollutant (no deterioration), then this term becomes 1. For vehicles with emissions below the 1975 standards the term will be greater than 1. Also, for any vehicles that met or exceeded the 1980 standards a bonus of 0.3 points was awarded; thus making the term equal to 2.5. The maximum possible score obtainable then is 2.5+0.2 for particulates or 2.7. The results for the AIRR Team vehicle are given in Table 4.

TABLE 4

Results of Emissions Tests During CACR

Pollutant Grams/mile	Cambridge Test Hot Open-7	Detroit Test Cold Closed-7	Pasadena Test Hot Open-7
HC	.151 (13ppm)	.70	-----
CO	29.3 (1.35%)	25.23	-----
NO	.232 (100ppm)	.78	-----
Particulates	.07	-----	-----

Applying these values to the emissions scoring formula results in an E factor of 0.76. No emissions data for scoring was taken at Pasadena because of a bearing failure in the synchronizer, which resulted in a lack of air being injected into the exhaust ports. If tested, the emissions of hydrocarbons and carbon monoxide would have been abnormally high and would not have been representative of the vehicle.

As it turned out; the emissions factor obtained, .76, was the highest reported of the gasoline powered cars in the race. The next highest score was 0.60. Even allowing for an increase in emissions of 20% over Boston figures, the resulting emissions factor would still have been .65. The class winner had an emissions score of 1.04, however the car used methanol for a fuel and during emissions testing aldehydes were not measured. It is also interesting to note that none of the gasoline fueled cars were able to meet the 1975 standards on the cold start with constant volume sampling, and Flame Ionization Detection for hydrocarbons.

2.5 Final Results in The Clean Air Car Race

The overall score is derived from a formula containing the scores from each of the various tests; performance, race, thermal efficiency, and emissions.

The formula used for determining the overall score is once again,

$$S = E(P + R + TE)$$

Where:

S = Total Score
E = Emissions Factor
P = Performance Score
R = Race Score
TE = Thermal Efficiency

The results are presented in Fig. 4. The final outcome was fourth place in the liquid fuel class.

These results indicate the overall level of performance of the AIRR Team vehicle. The driveability of the vehicle was excellent. There was no stumble, surge, or other driveability problems that have been associated to vehicles equipped with emissions control devices. There is a loss in power of the vehicle (10%-15%) which arises from the need for a greater throttle setting to maintain a given speed. This loss in power is due principally to exhaust gas recirculation. Fuel consumption also has increased slightly; 13 miles per gallon versus 14-15 for the unmodified vehicle. The emissions results during the race were not really representative of the capability of the emissions control system due to engine deterioration which will be explained in Section 3. To conclude, the vehicle has demonstrated that it is possible to significantly reduce pollutants while still maintaining good driveability. Table 5 gives typical operating characteristics of the vehicle during the race.

FIGURE 4

OVERALL SCORE IN CACE

$S = E(P + R + TE)$

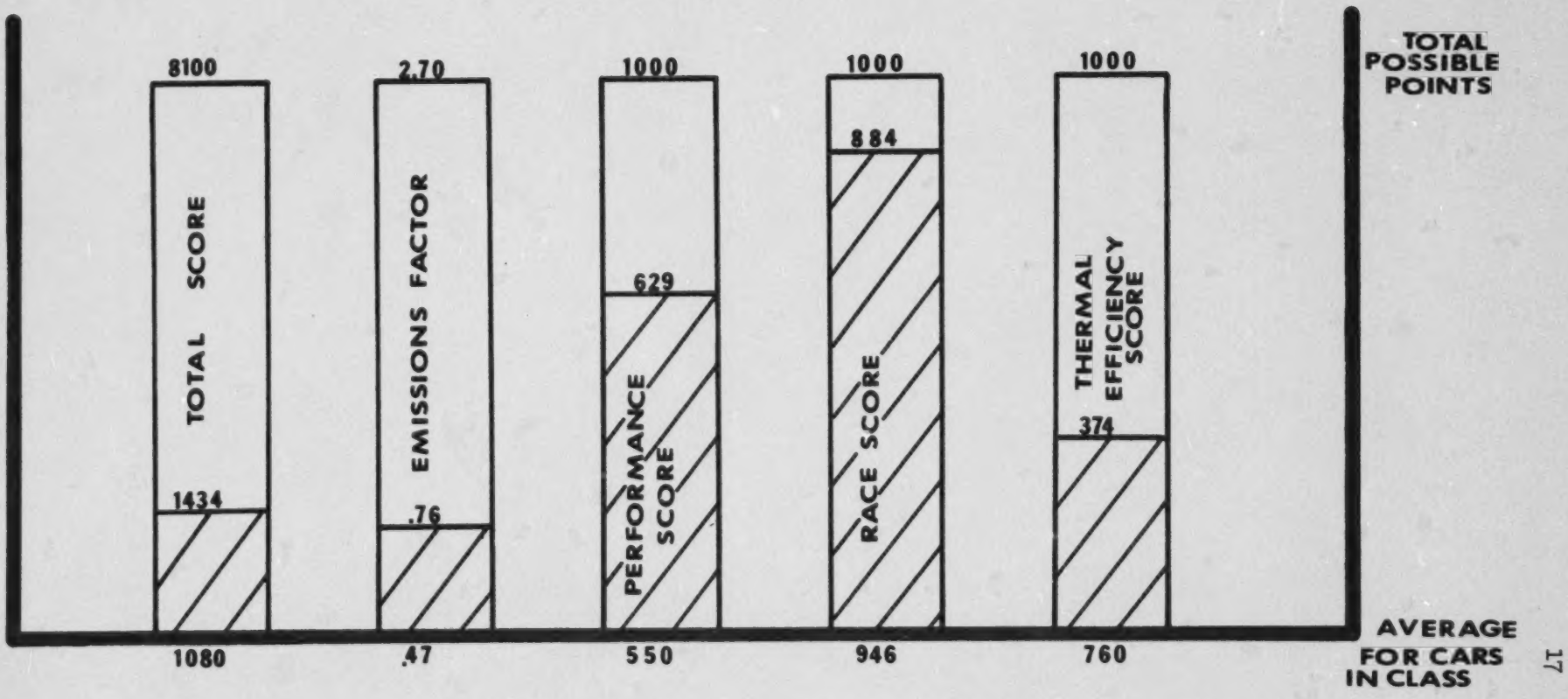


TABLE 5

Operating Characteristics Of The Vehicle
During The Race

Characteristics of Emissions Control System (60-70 miles per hour) ----

Thermal Reactors	1800 °F inside temperature 450 °F outside temperature
Catalytic Muffler	1500 °F at exit
Synchronizer Pressure	15-17 PSI
Exhaust Gas Recycle	1050 °F at exhaust pickup 175 °F at engine
Underhood	150 °F

Characteristics of Engine ----

Approximate Air-Fuel Ratio	13:1
Fast Idle Speed	1650 rpm
Idle Speed	800 rpm transmission in drive
Timing	5° ATDC
Vacuum Advance	NONE
Engine Speed	2450 rpm at 70 mph

Section 3

PROBLEMS ENCOUNTERED WITH THE VEHICLE

There were two problems encountered with the vehicle and both of these appeared during The Clean Air Car Race. The first occured in Detroit and the second occured outside of Champaign, Illinois.

The first problem occured on Wednesday morning, August 26. This was the morning after the cold start emissions test had been run. The problem manifested itself in the inability to start the vehicle. Work was continued until approximately 12:00 noon with no success in starting the car. At this point a call was made to Chrysler Corporation in Detroit for assistance. Subsequently, a mechanic was sent out to assist in starting the vehicle. All routine checks were made; carburation, timing, ignition components. A compression check was tried but it was difficult to get an accurate reading because of reactor interference. A call was again made to Chrysler and the car was subsequently towed to their lab.

The first problem found was a faulty starter which prevented sufficient cranking speeds; however, replacement with a new starter did not improve the startability of the car. The next step was to run a compression check. The results are shown below in Table 6.

TABLE 6

Results of Compression Test

Engine Mileage - 2268 Miles

LEFT BANK		RIGHT BANK	
Cyl No.	Compression (PSI)	Cyl. No.	Compression (PSI)
1	50	2	50
3	85	4	55
5	75	6	55
7	50	8	45

AVG. Compression - 58 PSI
Normal for Engine - 125 PSI

From the results of the compression check it was obvious that the car would not start due to a lack of air entering the engine from the low compression. The cause of the low compression was next to be determined. One means of doing this is to run a cylinder leakdown test. This involves pumping air into the cylinder with the piston at TDC with both valves closed and measuring the percent leakage. The result was about 88% leakage from the cylinders. Normal is considered to be between 5 and 10% for an engine. This meant that the leakage was either past the rings or past the valves. Valve recession had been considered to be the problem due to unleaded fuel and the high speed driving done. However, if the leakage was past the valves it would have come back either through the carburetor or out the tailpipe. Since the leakage was coming out the crankcase breather as blowby, it was felt that the problem was due to seized piston rings. A further attempt was made at trying to start the car by pouring about half a quart of oil down the carburetor to try and create a seal. After considerable effort and changing oil fouled plugs the car was started. It was subsequently shut down and it was not possible to restart it again.

The next day, Thursday the 27, the engine was torn down and it was found that all of the piston rings were cold seized and both piston skirts and bores were scored. The cold seizing accounted for the fact that once the engine was started it ran fairly well since with heat the rings would loosen up and effect somewhat of a seal. This also correlated with the observation that the car had been getting progressively harder to start when cold, or after short peroids of rest.

The cause of the ring failure appeared to be due to particulate matter entering the cylinders. This was evidenced by particles in the ring grooves and abrasive wear of the valve stems, pistons, and bores. This material was thought to be the insulation which came out of the reactors and returned to the engine both through the exhaust gas re-circulation line and camshaft overlap. However, the actual cause of the failure was to be determined after returning to Berkeley where a teardown of the emissions system and analysis of the particulate material could be effected. A discussion of the teardown and analysis is in Section 5.

A new engine was donated by Chrysler Engineering and it was installed along with the emissions control equipment. The emissions control equipment was bolted to the new engine without any modifications. A low velocity filter supplied by Chrysler was installed in the recycle line in an attempt to prevent damage to the new engine. However, the filter is experimental itself and a measure of its effectiveness was not available.

Work was finally completed and the catch up phase of the race was begun at 12 midnight Thursday August 28.

Section 4

EMISSIONS TESTING

A discussion of emissions testing of the AIRR Team vehicle is presented in this section. The discussion is divided into pre-race testing and testing during the race.

4.1 Pre-Race Emissions Testing

Initial emissions testing was done at Chevron Research, Richmond, California. The facilities included a Clayton Chasis Dynamometer and Non-Dispersive Infrared Analyzers (NDIR) for continuous measuring of unburned hydrocarbons, carbon monoxide, and nitrogen oxides. The Driving Cycle specified by the Federal Register Vol. 33, No. 108 was followed. Test runs consisted of hot start, open 7 mode cycles (Table 7). Open testing refers to sampling from the exhaust during portions of the cycle analyzing for concentrations continuously, and assigning a weighing factor to account for the contribution of a particular mode to the overall emissions.

TABLE 7.

Driving Cycle Used During Emissions Testing

Sequence No.	Mode	Acceleration, mph/sec.	Time in Mode, Seconds	Cumulative Time, Seconds	Weighting Factor
1	Idle		20	20	0.042
2	0-25	2.2	11.5 } 14	31.5	0.244
3	25-30	2.2	2.5 }	34	Omitted
4	30		15	49	0.118
5	30-15	-1.4	11	60	0.062
6	15		15	75	0.050
7	15-30	1.2	12.5 } 29	87.5	0.455
8	30-50	1.2	16.5 }	104	Omitted
9	50-20	-1.2	25	129	0.029
10	20-0	-2.5	8	137	Omitted

The emissions of the vehicle before modification were 1.84 grams/mile unburned hydrocarbons, 7.83 grams/mile carbon monoxide, and 5.93 grams/mile oxide of nitrogen (5). Several cycles were run to make initial settings. Table 8 shows the results for three cycles.

TABLE 8

Results of Emissions Tests At Chevron Research

Test No.	Hydrocarbons		Carbon Monoxide		Nitrogen Oxide		Comments
	PPM	gm/mile	%	gm/mile	PPM	gm/mile	
1	20.95	.266	.013	.316	397.3	1.03	Recycle valve half open
2	28.7	.355	.026	.631	249.1	.69	Full Recycle about 15%
3	62.67	.795	.573	13.65	not measured		Ahead of Catalytic Muffler

It should be noted that for these tests the exhaust gas recirculation system used was the log manifold system which was later discarded in favor of the carburetor plate.

Run 3 is interesting since it indicated the relative effectiveness of the thermal reactor and the catalytic muffler. Although the reduction of unburned hydrocarbons is significant, the large reduction of CO by the catalytic muffler is indicative of its potential for reduction of this pollutant.

The engine was operated with standard jets, no vacuum advance and 5 degrees initial ignition retard.

These tests were run with under 200 miles on the engine and available time for testing was very limited. However, these initial results proved very encouraging.

Emissions testing was continued at the Air Resourced Board in Los Angeles where several cycles were run. Here NDIR's were also used to measure pollutants. The log manifold was still being used, with the addition of a throttle connected butterfly to help driveability. Five cycles were run and the fourth and fifth were averaged. Timing and carburetor settings were essentially the same as on previous tests. The results are given in Table 9.

TABLE 9

Results of Emissions Tests at Air Resources Board

July 17- 1970

Test No.	Hydrocarbons PPM	Carbon Monoxide %	Nitrogen Oxide PPM
1	25	.10	343
2	25	.10	353
Avg. 1 and 2	25	.10	375*
in gms/mile	.29	2.17	.866

* Includes correction for humidity

Carbon monoxide and nitrogen oxide levels had increased. This was associated with poor driveability, caused by sticking open of the on-off solenoid valve in the recycle line. Surge and stumble were severe and caused difficulty in running the tests. The hydrocarbon emissions however were not appreciably affected, indicating good conversion by the thermal reactors.

Since control of the recycle system was becoming erratic the decision was made to change over to the carburetor plate before the emission certification test at the NAPCA Laboratory in Los Angeles.

The carburetor plate was installed and the log manifold recycle system removed. No testing of this system had been done prior to certification testing at NAPCA in Los Angeles. The results of the certification tests are given in Table 10.

TABLE 10

Results of Emission Testing at NAPCA

gms/mile

Hydrocarbons	Carbon Monoxide	Nitrogen Oxide
.16	8.9	.75
1975 proposed standards		
.50	11.0	.90

Emissions were measured using Beckman NDIR analyzers. For qualification in the race emissions had to be below or equal to 1975 Proposed Federal standards. An interesting observation was that if the amount of exhaust gases recycled was reduced, thus increasing the NO, there was a reduction in the CO. Conversely, if the amount recycled was increased there would be a reduction in NO as expected, but also an increase in CO. The possibility of the catalytic muffler deteriorating was considered; and, to be safe the spare catalytic muffler was installed prior to departing for Boston. The new recycle system functioned excellently, no driveability problems were encountered with it.

The next emissions tests were done at Chrysler Corporation in Detroit while in route to Cambridge, Massachusettes. A full day's testing was done and adjustments were made to the carburetion. Standard jets and smaller diameter metering rods were installed and the spring controlling the lifting of the metering rods was weakened. Normally the rods

lift at 10-12 inches of engine vacuum on the first step and lift again when vacuum drops below 5 inches. Since the car is operating at reduced engine vacuum due to exhaust gas recirculation, the metering rods were lifting form the jets the majority of the time increasing the fuel fed to the engine. Results of open seven mode hot starts is below in Table 11.

TABLE 11

Results of Emissions Tests at Chrysler

Test No.	Hydrocarbons		Carbon Monoxide		Nitrogen Oxide		Remarks
	PPM	g/mi	%	g/mi	PPM	g/mi	
1	16	.18	.23	5.0	187	.67	Standard jets
2	9	.10	.20	4.3	195	.69	Standard jets with smaller diameter metering rods
3	8	.09	.18	3.9	160	.56	Idle speed and mixture adjustment
4	6	.07	.16	3.5	161	.57	Weaker metering rod spring

The results of testing at Chrysler were very encouraging. The car ran extremely well and presented no driveability problems.

One final opportunity for testing before official testing, was done in Cambridge using Ford's mobile emissions laboratory. The results were comparable to those obtained at Chrysler.

4.2 Emissions Testing During the Race

During the course of the Clean Air Car Race emissions were measured three times. A hot start, open 7 - mode test in Cambridge and Pasadena and a cold start, closed 7 - mode cycle test in Detroit.

For the tests in Cambridge and Pasadena emissions of HC, CO, and NO_x were reported in concentration terms. The Cambridge and Pasadena tests

were used to determine the deterioration factor in the emissions scoring formula. Based on instrument sensitivity the minimum values of emissions reported were 10 ppm for HC, .1% for CO and 100 ppm for NO_x.

In conjunction with the tests in Cambridge and Pasadena, particulates also were sampled. This was done by taking a 1 cfm sample from the exhaust and filtering it with a glass fiber filter with a 99% collecting efficiency for particles over 0.3 micron diameter. To prevent condensation, the filter was heated to 100°C. The particulate mass was then obtained by tare weighing. A calibration curve relating exhaust volume times the sample weight to the particulate emissions was used to obtain grams per mile of particulates.

The cold start, closed 7 - mode cycle, test in Detroit employed a constant volume sampler (CVS) to measure emissions. The use of CVS gives emissions values in grams per mile directly and will be the basis for measuring emissions commencing in 1972. The cold start consisted of a minimum 4 hour cool down of the vehicle before testing. Minimum values reported due to instrument sensitivity were .125 gram per mile for HC; 1 gram per mile for CO; and .2 grams per mile for NO_x. Emission values obtained from this test were the basic emission numbers used in the emissions scoring formula.

TABLE 12

Results of Emissions Test at Cambridge

Hydrocarbons		Carbon Monoxide		Nitrogen Oxide	
PPM	gm/mile	%	gm/mile	PPM	gm/mile
13	.15	1.35	29.4	100	.232

Particulates were .07 gm/mile

The results of the Cambridge tests are shown in Table 12. The cause of the extremely high CO has remained partially unexplained. However, after this test the carburetor was checked and several mounting bolts had loosened. This could have caused a vacuum leak, which would result in a decrease of the A/F ratio. This is reasonable in view of the extremely low NO reported. The actual reading from the instrument was 34 ppm NO: but since this was below instrument sevsitivity, the value reported was 100 ppm.

The cold test in Detroit was the next emission test to be performed. The test was performed at the NAPCA facility in Willow Run. In conjunction with the Constant Volume Sampling a continuous sample was also taken and measured according to existing 1970 Federal procedure. The results are in Table 13 below.

TABLE 13

Results of Emission Tests at Detroit

Cold Start - gms/mile

	Hydrocarbon	Carbon Monoxide	Nitrogen Oxide
Closed - 7 with Constant volume sampling	.70	25.23	.78
Continuous open - 7	.25	5.60	.45

This was the first cold start emissions test performed on the vehicle and the results of the continuous sample were 50% below the 1975 standards. The lower CO value than that obtained in Cambridge (29.4 grams per mile in Cambridge versus 5.60 grams per mile in Detroit) plus the fact that the Cambridge test was a hot start while the Detroit a cold start seems to substantiate the carburetor

malfunction being responsible for the high CO in Cambridge.

The CVS results shown are extremely high especially for CO. Emissions were expected to have increased since the combination of Constant Volume Sampling and the use of the Flame Ionization Detector for measuring hydrocarbons results in greater emissions levels than those obtained from a continuous test with NDIR's. However the increase was greater than expected and indicated a malfunction of the vehicle. As it turned out these tests were run with an engine that had seriously deteriorated and shortly afterward failed to start due to ring seizure. The engine deterioration resulted in having to crank the engine and pump the throttle for nearly 20 seconds to start it. This did not affect the continuous sample but the constant volume sample procedure samples as soon as cranking begins. Thus raw fuel was being pumpted into the sample bag. Furthermore, with a condition of sticking rings large amouts of blow-by is present. This blow-by re-entering the engine would tend to decrease the air fuel ratio and hence increase CO, which is a function mainly of air fuel ration (6). Similarly a large increase in hydrocarbons would be expected, but a change in the air fuel ratio generally causes CO to increase more rapidly than hydrocarbons (7). Also the conversion of hydrocarbons is accomplished more readily by the thermal reactor and it is able to handle greater concentrations of hydrocarbons before being overwhelmed.

A further possible explanation for the high CO which would also account for the increase in CO with increased recycle (Fig - 5) is due to the reduction of peak temperature and pressure in the cylinder when recycling.

FIGURE 5

SUMMARY OF HOT START EMISSIONS TESTS

Test 1. Chevron Research
Test 2. Air Resources Board
Test 3. NAPCA - L.A., Certification
Test 4. Chrysler - Detroit
Test 5. Cambridge
Test 6. Chrysler - Detroit, New Engine

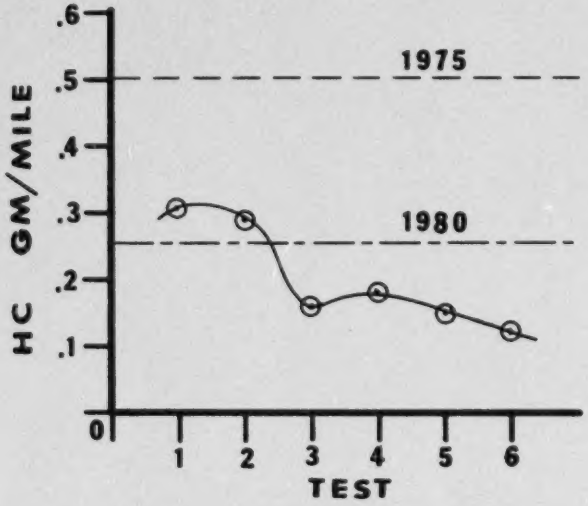


Fig. 5a
Unburned Hydrocarbons

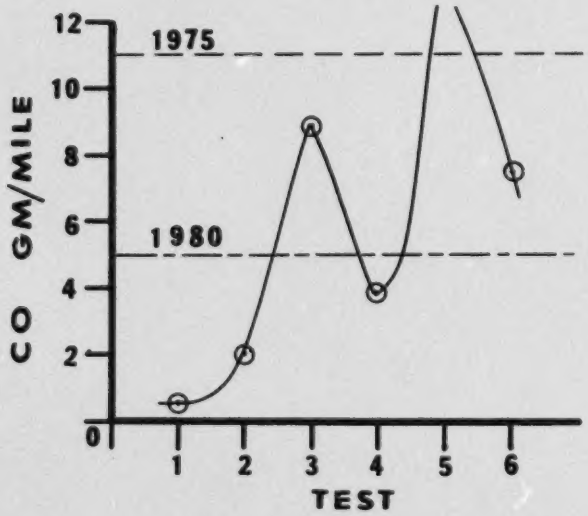


Fig. 5b Carbon Monoxide

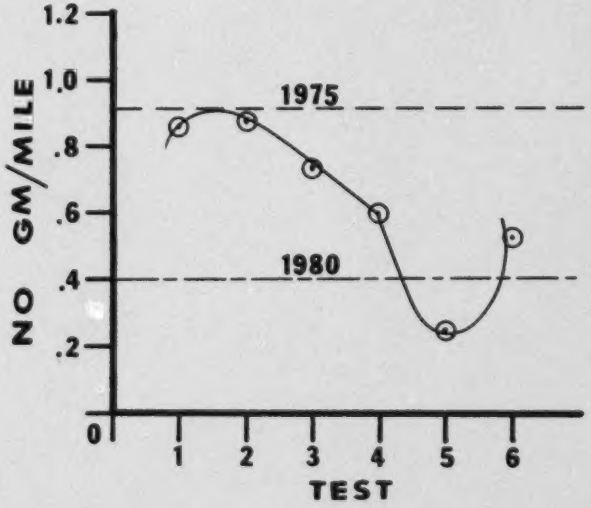


Fig. 5c Nitrogen Oxides

Since the principle reaction for the disappearance of CO is considered to be $CO + OH \rightleftharpoons CO_2 + H$ (8), a reduction of temperature and pressure would tend to impede or inhibit the disappearance of CO. A combination of the effects mentioned and suspected deterioration of the catalytic muffler is the cause of the erratic CO emissions.

After installation of the new engine, a hot open-7 mode test was conducted: The results are below in Table 14.

TABLE 14

Results of Emissions Test On New Engine

Hydrocarbons		Carbon Monoxide		Nitrogen Oxides	
PPM	GM/MILE	%	GM/MILE	PPM	GM/MILE
11	.127	.36	7.82	160	.56

The final emission test in Pasadena was not run due to the synchronizer bearing failure as mentioned in Section 3. However, a cold start test using an open-7 mode procedure was run in Los Angeles without air injection. The results in Table 15 indicates the effectiveness of the timed air injection system used in the vehicle.

TABLE 15

Results of Emissions Test With no Air Injection

	Hydrocarbons		Carbon Monoxide		Nitrogen Oxides	
	PPM	GM/MILE	%	GM/MILE	PPM	GM/MILE
Average Cycle 1-4	504.9		5.97		---	
Average Cycle 6-7	63.5		3.58		---	
Composite	217.9	2.52	4.41	95.94	---	---
Detroit Test With Air Injection		.25		5.60		.45

Unfortunately, as of this writing there has been no emissions tests conducted with the emissions control system since it has been disassembled and subsequently reinstalled in the vehicle.

Throughout the emissions testing, the performance of the emissions control system was excellent. During the cold start test, the reactors reached conversion temperatures in about 45 seconds. The driveability of the vehicle was excellent with no surge or stumble present. The only major problem encountered was the deterioration and subsequent failure of the engine.

Table 16 and Fig. 6 are summaries of the emissions testing done on the vehicle. Figure 6 shows that for a cold start emissions test done according to existing procedures (1970 Federal), the levels of pollutants were approximately 50 per cent below 1975 proposed Federal standards. This was without the benefit for evaporative control systems specified in the Federal Register (9).

TABLE 16

SUMMARY OF EMISSIONS TESTING

Location	Date	Emissions in GMS / MILE HC	CO	NO	Particulates
Air Resources Board [1]	7/17/70	.29	2.17	.866	----------
NAPCA Los Angeles [1]	7/28/70	.16	8.9	.75	----------
Chrysler Corporation [1]	8/11/70	.07	3.5	.57	----------
Cambridge [1]	8/18/ 70	.15	29.4	.232	.07
NAPCA Willow Run	8/25/70				
CVS [2]		.70	25.23	.78	----------
Continuous [3]		.25	5.60	.45	----------
Chrysler New Engine [1]	8/27/70	.127	7.82	.56	----------
1975 Proposed Standards		.50	11.0	.90	.1
1980 Proposed Standards		.25	4.7	.40	.03

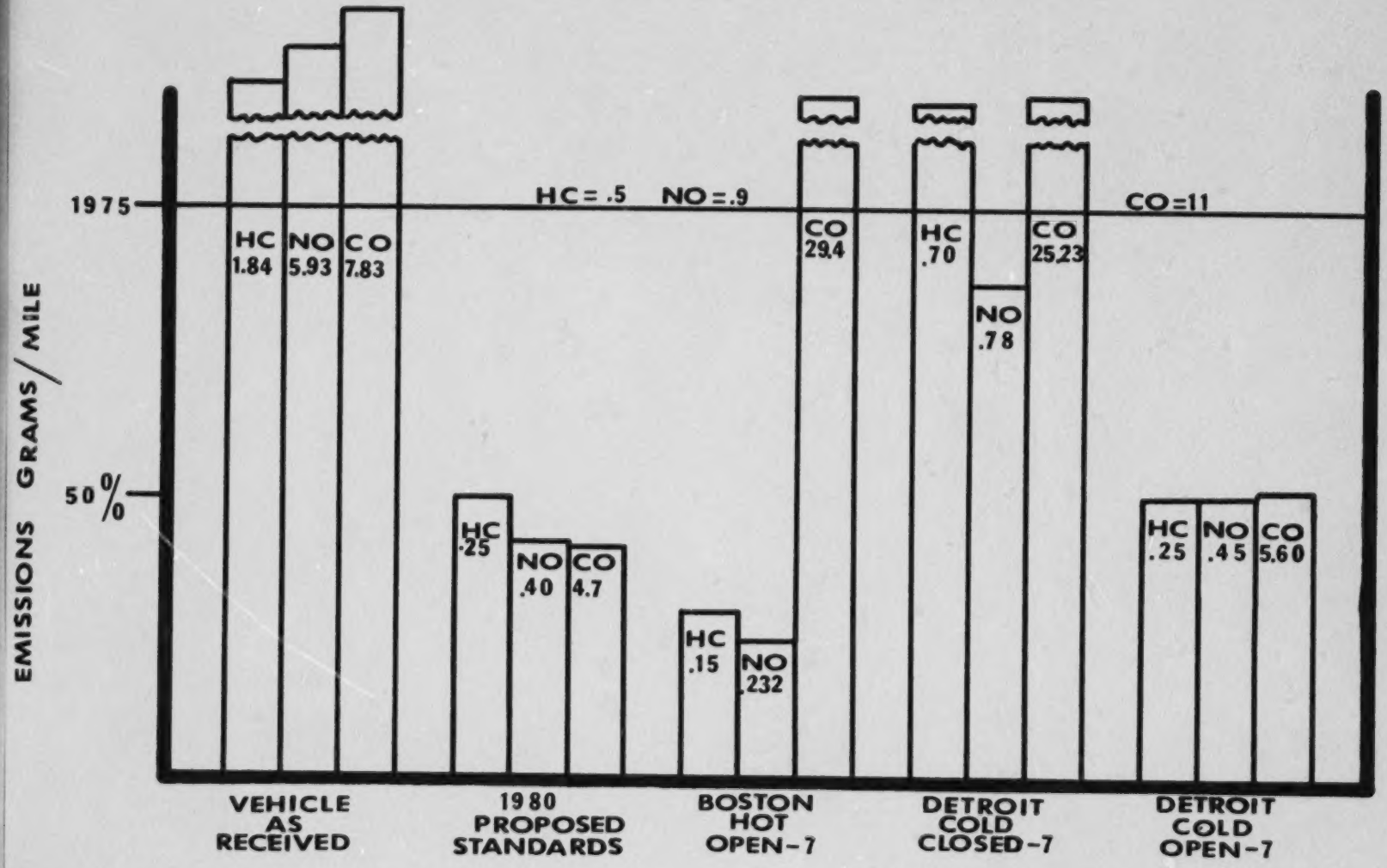
1) These tests consisted of an open seven mode cycle combined with a hot start. The emissions values are not corrected for evaporative control system equipment.

2) This test is a closed seven mode using constant volume sampling and FID, with a cold start.

3) This test was a open seven mode cold start done in conjunction with CVS test.

FIGURE 6

RESULTS OF EMISSIONS TESTS DURING CACR



Section 5

POST RACE TEARDOWN AND ANALYSIS OF EMISSIONS CONTROL SYSTEM

Upon returning to Berkeley, the Emissions Control System was completely disassembled for inspection. The system had accumulated 5735 miles; 2268 of these being on the first engine and the balance, 3467 miles,on the replacement engine. The majority of the mileage on the vehicle comprises high speed, 70 mile per hour, turnpike driving.

This section covers the teardown and analysis of the Emissions Control System and the modifications that were made to it.

5.1 Analysis of the Thermal Reactors

Figure 7 shows the left thermal reactor after disassembly. The cause of the insulation erosion is immediately evident. The 16 mil stainless steel used to contain the Kao-Wool insulation was severly warped. This warpage allowed the turbulent exhaust gases to come into intimate contact with the insulation causing it's subsequent erosion and re-entry into the engine. As can be seen in Fig. 7, the insulation is badly burned and broken up. The total loss of insulation however appeared to be minimal and is estimated at 5 to 10 per cent. The Inconel core and its associated runners and the air injection tubes showed no signs of appreciable deterioration.

5.2 Analysis of Recycle System

The removal and inspection of the exhaust gas recirculation system revealed accumulations of particulate material along the walls of the copper recycle line and within the filter. Figure 8 shows the filter

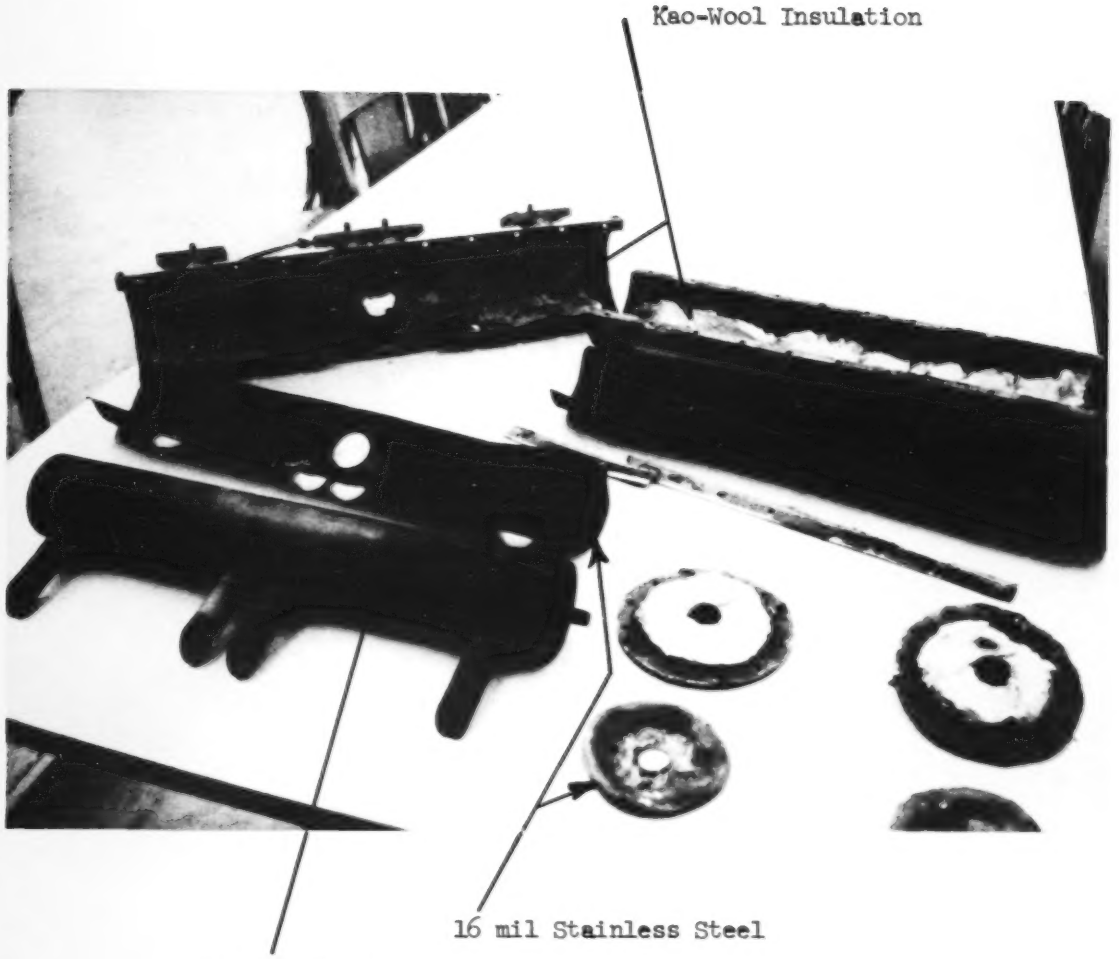


FIGURE 7 - Left Thermal Reactor Showing Warpage of Stainless Steel and Erosion of Insulation

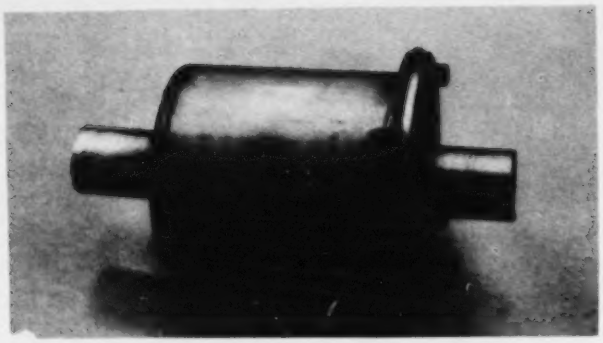


Fig. 8a
Exhaust Gas Filter

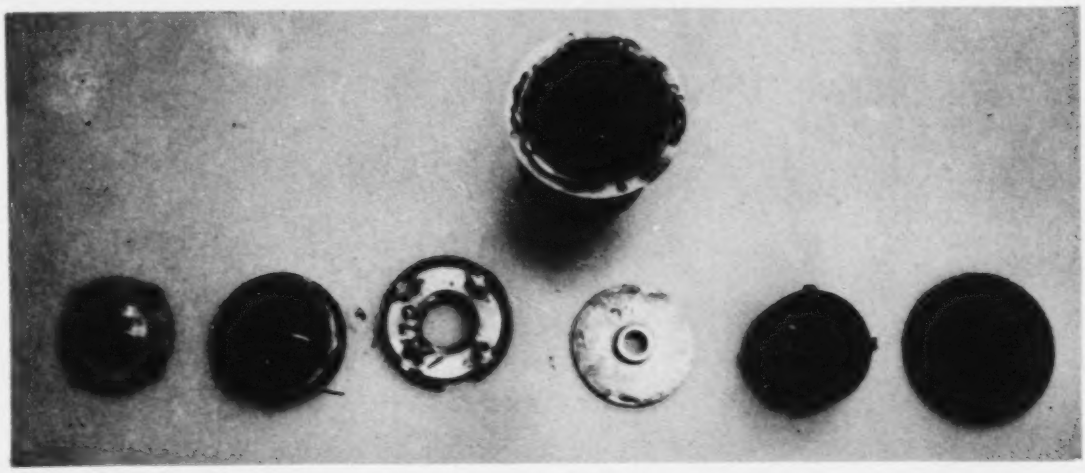


Fig. 8b - Internal Components of Exhaust Gas Filter

Fig. 8c
Material Recovered From Exhaust Gas Filter

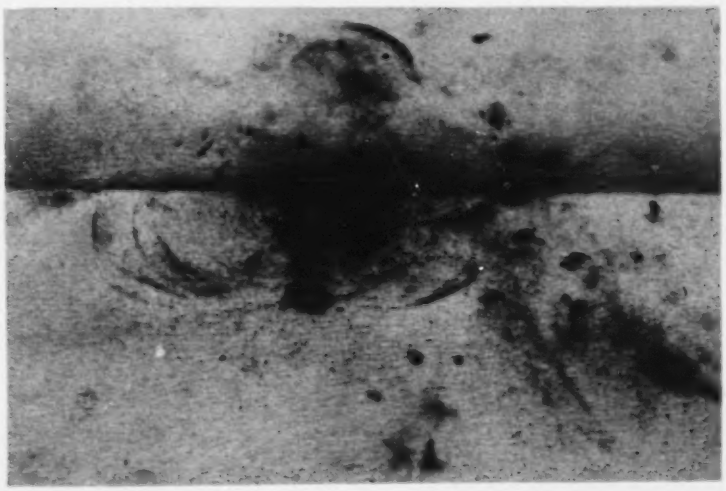


FIGURE 8 - Exhaust Gas Filter and Material Recovered From It

and the material recovered from it. As can be seen the material consists of burned particulates along with some fibrous material. Although the amount of material obtained is considerable, the weight of it amounts to less than an ounce. The filter appeared to be quite effective since negligible quantities of particulates were found in the line from the filter to the carburetor plate. Since this filter was not used on the first engine, it is reasonable to conclude that the material removed from the filter was the cause of the failure of the engine.

The next step was to determine if this material was indeed the insulation from the reactors as suspected. To verify this, a Spectrochemical Analysis was done by Chevron Reasearch on a sample of the material obtained from the exhaust gas recirculation line and on a sample of the Kao-Wool insulation. The results of this analysis is given in Table 17.

The Kao-Wool is composed principally of Aluminum and Silicon. These two elements account for almost 50% of it's composition; the remainder being oxygen and traces of the other elements shown. As can be seen from Table 17, the exhaust gas recirculation line sample has a high percentage of Aluminum and Silicon thus verifying that the material which resulted in the engine failure was the insulation from the reactors re-entering the engine.

Of further interest is the amount of other elements present in the sample tested. The silver present is due to the melting of the silver solder used in assembling the exhaust gas recirculation line. The copper was probably from flaking of the copper line used to recycle the exhaust gases. The large quantity of Iron present is due to material

TABLE 1

Spectrochemical Analysis of Kao-Wool Insulation
and Sample From Exhaust Gas Filter

Test Conducted 9/22/70

Element	Weight - % Sample	
	Kao-Wool	Exhaust Gas Filter
Silver (Ag)	*******	0.0173
Aluminum (Al)	12.6357	6.5679
Barium (Ba)	0.0442	0.1777
Chromium (Cr)	*******	0.5023
Copper (Cu)	*******	2.7146
Iron (Fe)	0.4974	29.7052
Magnesium (Mg)	0.0046	0.0229
Manganese (Mn)	*******	0.2631
Sodium (Na)	*******	0.1119
Nickel (Ni)	*******	1.0463
Lead (Pb)	*******	0.7146
Silicon (Si)	35.4233	13.5331
Tin (Sn)	*******	0.3578
Titanium (Ti)	0.7669	0.3997
Vanadium (Va)	0.0566	0.0983
Zinc (Zn)	1.5302	1.0761

removed from the exhaust pipe at elevated temperatures. The presence of these materials is indicative of the high temperatures encountered in the exhaust line, and indicates that vehicles using emissions control devices which result in high exhaust temperatures will probably have to use stainless steel in their exhaust line.

Figure 9 shows one of the pistons and the rings from the first engine. The scuffing of the piston skirt indicates the abrasive wear caused by the insulation re-entering the engine. Also, the rings show the material which accumulated in them causing their seizure (see top ring). As indicated this material proved to be the thermal reactor insulating material. The rings were broken during removal.

5.3 Analysis of Synchronized Air Injection System

Upon disassembly of the synchronizer, it was apparent that the bearing failure was caused by backflow of hot exhaust while the air pump was inoperative, see Fig. 10. Because of the bearing failure, the majority of the air being pumped into the synchronizer, after installation of a replacement air pump, was coming out the front of the synchronizer through the bearing. The accumulation of carbon deposits from exhaust backflow also is evident.

The cause of the air pump failure was thought to be bearing failure resulting from the high temperatures due to running at increased pressure; thus causing the bearing lubricant to run out. However, upon inspection it was found that the bearings were sufficiently lubricated and that the failure of the air pump was a result of excessive wear of the carbon vanes in the pump.

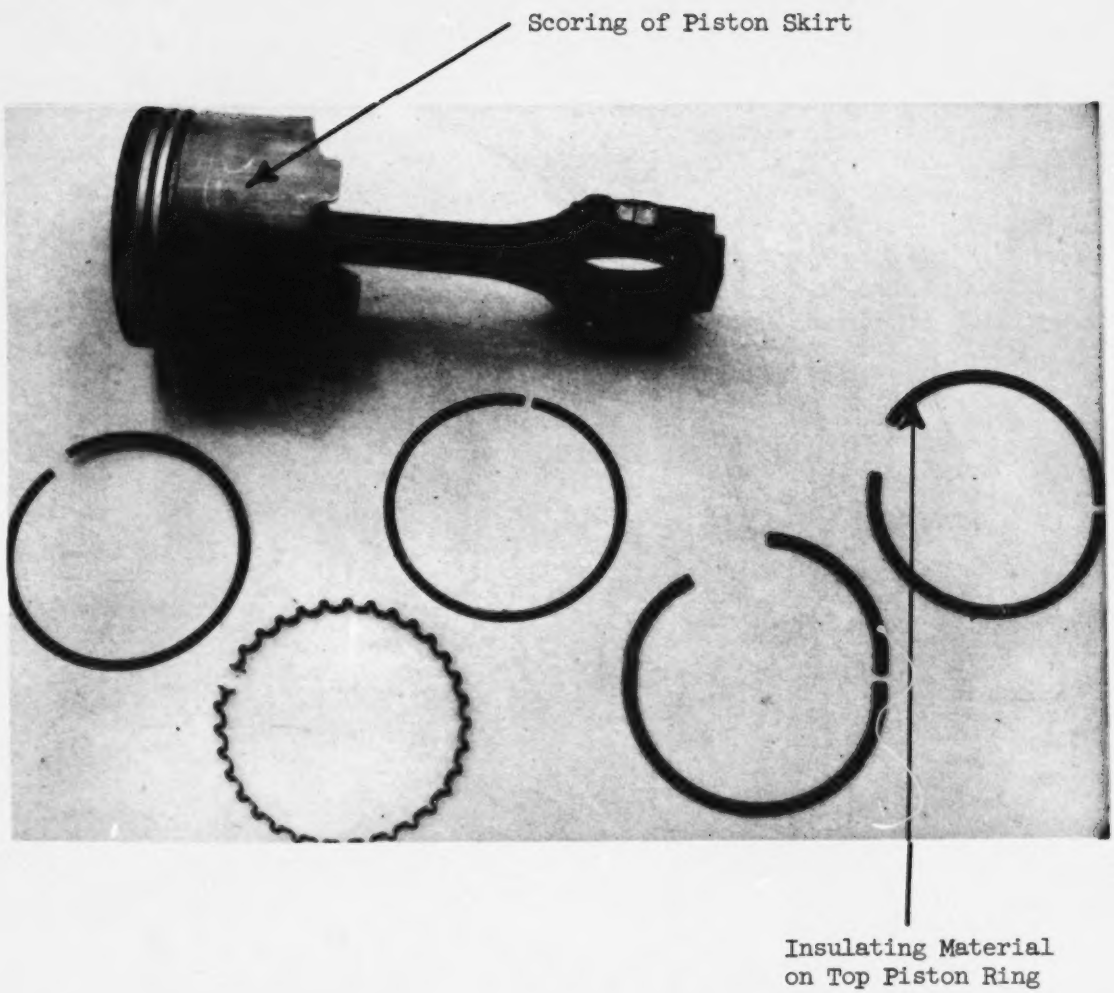


FIGURE 9 - Piston and Ring From First Engine Showing Damage Caused by Insulating Material Reentering Engine

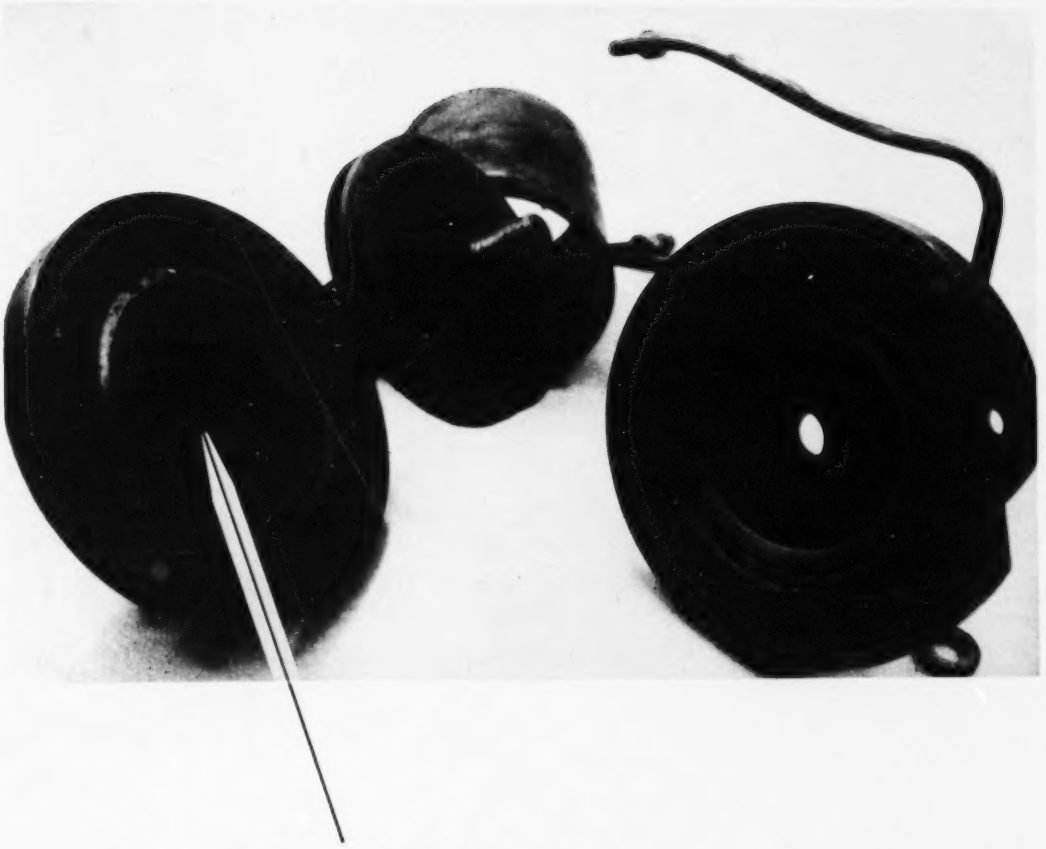


FIGURE 10 - Disassembled Synchronizer Showing Bearing Failure

5.4 Condition of The Engine

Since the first engine failed after 2268 miles and the second had 3467 miles on it, there was some speculation as to the condition of the engine. To check this, a compression test was done. The results are given in Table 18.

TABLE 18

Result of Compression Test
Second Engine - 3467 Miles

Left Bank		Right Bank	
Cylinder	Compression (PSI)	Cylinder	Compression (PSI)
1	136	2	142
3	134	4	140
5	130	6	138
7	130	8	144

Average Compression 136 PSI
Normal For Engine 125 PSI

These results indicated the engine was in good condition and also that the filter had been effective in removing particulates from the exhaust gas recirculation line.

5.5 Reinstallation of the Emissions Control System

The only major post-race change to the emissions control system concerned the thermal reactors. To try to eliminate the need for insulating the reactors the possibility of using a radiation shield in conjunction with an air space was investigated. The results indicated that a radiation shield and air gap would be feasible, but would increase the temperature of the outer shell approximately 150 to 200 degrees Fahrenheit. If

suitable shielding were provided for critical components near the reactors, this temperature increase would present no problems. As a result of the investigation, the reactors were reassembled using a radiation shield and air space in place of the insulation previously used.

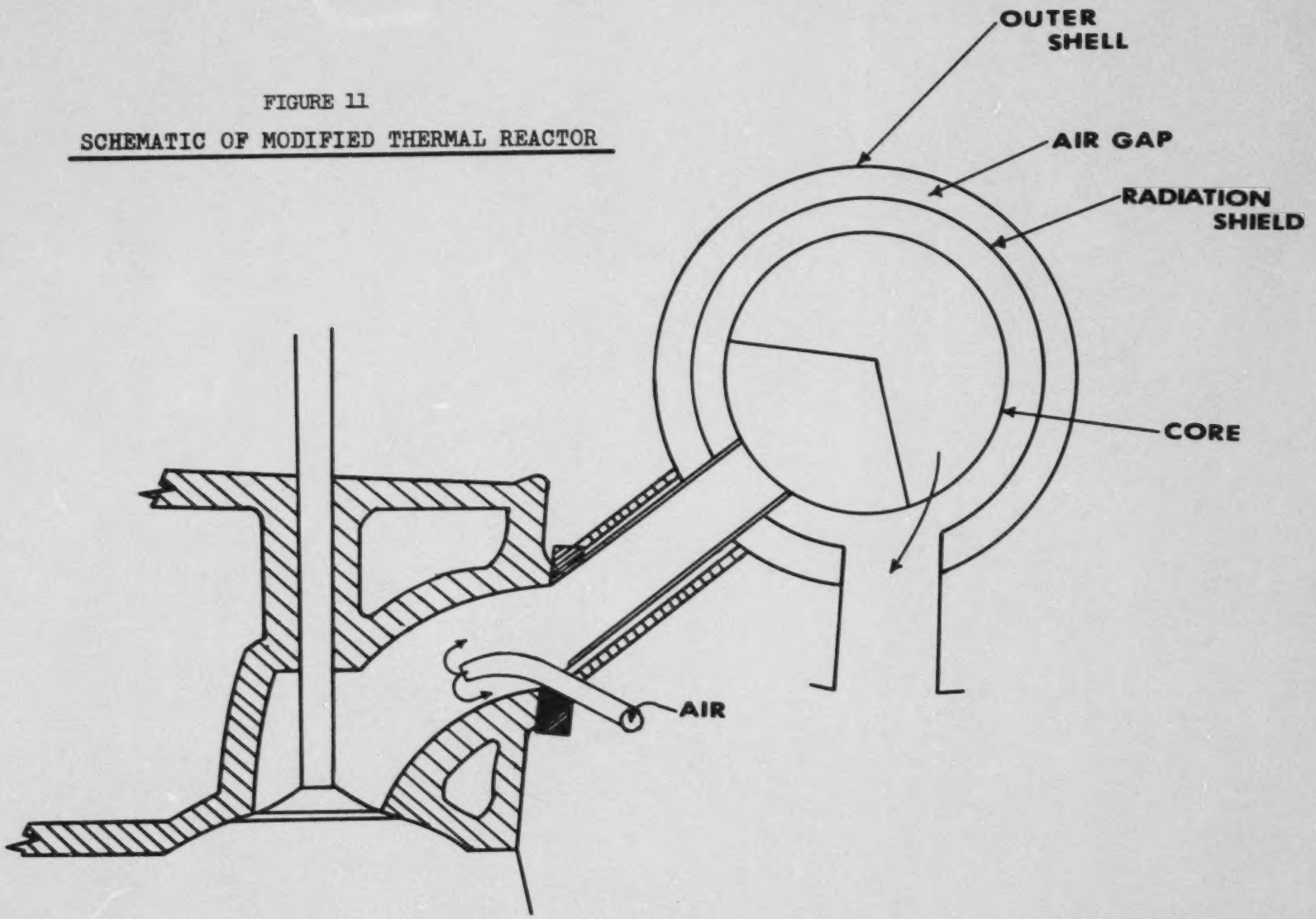
Figure 11 shows the present reactor configuration using the radiation shield and air space. The shield made of .031 stainless steel completely encloses the internal core and is loosely mounted using the pins on the ends of the core to allow freedom of movement for expansion and contraction. The reactors used throughout the race were so modified, reassembled, and installed in the vehicle along with the other emissions control equipment.

5.6 Present System

Figure 12 shows the emissions control system in its present form. The only significant change made was to the reactors as mentioned, and the addition of the exhaust gas filter. The window washer was relocated to provide room for the exhaust gas filter and some shielding was done to components near the reactors. Figure 13 shows the system installed in the vehicle prior to the race and the system as it is presently. The operating characteristics of the present system is given in Table 29.

FIGURE 11

SCHEMATIC OF MODIFIED THERMAL REACTOR



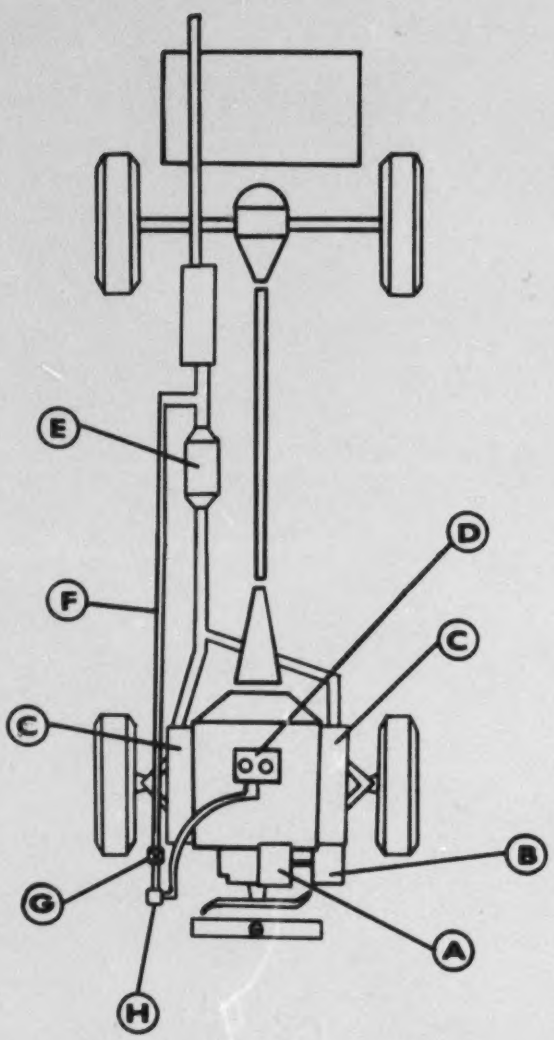


FIGURE 12

SCHEMATIC REPRESENTATION
OF
EMISSIONS CONTROL SYSTEM

CONTROL OF HYDROCARBONS AND CARBON MONOXIDE

A- AIR PUMP

B- SYNCHRONIZER

C- THERMAL REACTOR

E - CATALYTIC MUFFLER

CONTROL OF NITROGEN OXIDE

F - EXHAUST GAS RECYCLE LINE

G - CONTROL VALVE

H - EXHAUST GAS FILTER

D - CARBURETOR PLATE

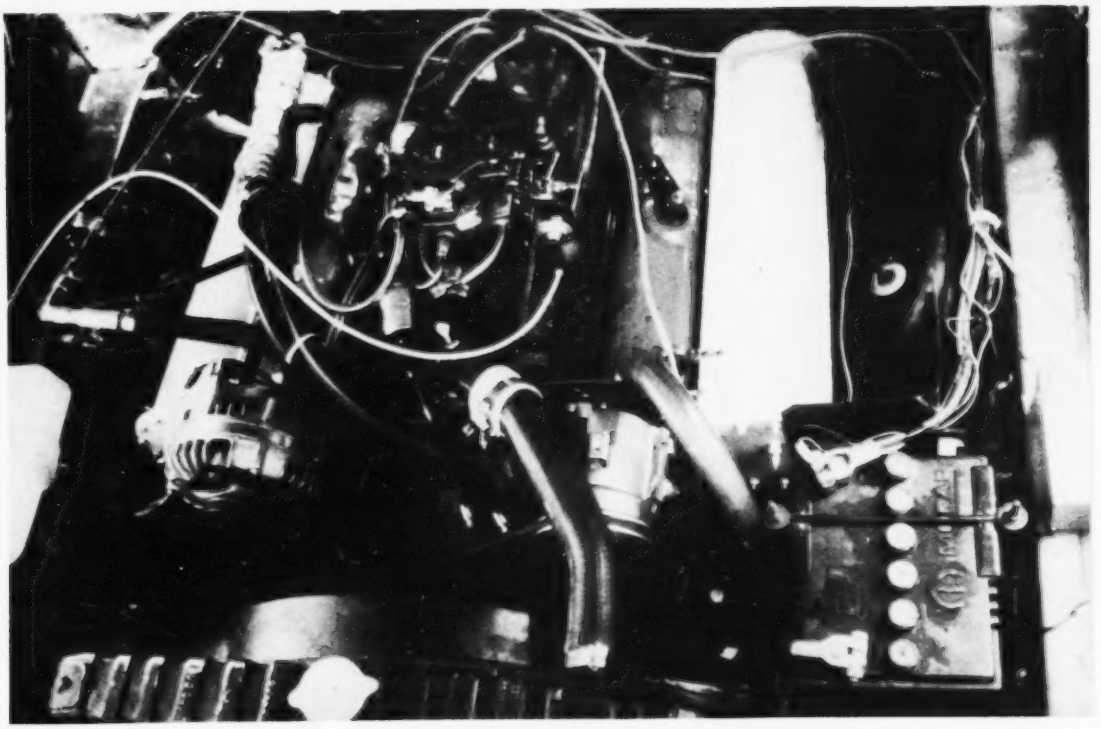


Fig. 13a - System prior to Race

Fig. 13b - System After Modification

FIGURE 13- EMISSIONS CONTROL SYSTEM INSTALLED IN VEHICLE

TABLE 19

OPERATING CHARACTERISTICS OF VEHICLE [1]

Speed (mph)	Average Reactor Temperature (°F)	Average Reactor External Temperature (°F)	Catalytic Muffler Temperature (°F)	Recycle Temperature At exhaust (°F)	Recycle Temperature At engine (°F)	Underhood Temperature (°F)	Synchronizer Pressure (PSI)
Idle [2]	1250	450	1025	850	100	200	2
20	1425	300	1000	800	100	150	5 - 6
30	1500	350	1100	780	100	130	8
40	1575	400	1200	750	100	120	9 - 10
50	1625	475	1300	800	100	140	13 - 14
60	1700	525	1350	980	100	120	15
70	1800	600	1400	1050	100	120	17 - 18

1) These values can vary depending on how car is driven (particularly Reactor temperature).

2) This is after highway cruising and allowing engine to idle for five minutes at 700 RPM in gear.

Section 6

SUMMARY AND CONCLUSION

The performance of the AIRR Team vehicle in over six thousand miles of driving demonstrates the potential of it's low emissions control system in reducing pollutants. The complete system was designed built and installed in the vehicle in a little over two months at a total cost of about $4500. Only one month was available for testing and tuning of the vehicle. Had more time been available, the problems encountered during the race would have occured before the race and would have been corrected. Despite this shortage of time for development the vehicle has proven to be quite reliable and is presently in normal use at the University. Even with the engine failure, the vehicle was able to demonstrate that it was capable of reducing pollutants to 50 per cent below the 1975 proposed Federal standards during a cold start open seven mode test. The vehicle is presently in use at the University of California and will provide an incentive for future student participation in reducing pollutants from the automobile.

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